Interaction of above/below urban grounds: an experimental facility developed to analyse computer modelling results

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Abstract

This research undertaken at the University of Sheffield aims to provide a better understanding of the interaction above/below ground urban floods. A newly constructed unique experimental facility has been developed in the water lab, and it includes a sewer system, composed by 3 main pipes, 6 manholes and a CSO (Combined Sewer Overflow), and a preliminary urban surface with the slope 1/1000. This paper describes the experimental facility that has been built, how the system is managed in real time control using Labview software, which methodology will be applied to increase the understanding of the exchange flow-rate between an urban surface and a below sewer system and it presents preliminary results obtained comparing physical results with computer software results such as InfoWorks, SWMM and SIPSON (NUNO MELO et al., 2012). Finally, the PIV system (Particle Image Velocimetry) that will be used for the acquisition of the images during the event of flooding is briefly explained. This last step will be useful for the comparison between 3D digital maps created by standard software against real physical results.

Keywords

Drainage; Flooding; Physical Modeling; Computer Modeling; Discharge coefficients.

INTRODUCTION

Pluvial flooding occurs when storm water overwhelms the capacity of the local drainage or storm water system. These episodes are usually caused by high intensity short duration storms, weather fronts of this nature of this type are difficult to forecast with accuracy at lead times greater than a few minutes (LIGUORI et al, 2012) therefore providing warning and/or adequate defence is very difficult (Pitt Review, 2008).
During pluvial flood events water in sewage systems or storm water drains surcharges onto street level, interacting with surface water via manholes and gully's. Pluvial flooding causes significant long term damage to residual and commercial areas, economic disruption, danger to life and social upheaval.
The frequency and severity of pluvial flood events is expected to increase worldwide due to some important factors:

- climate change, with heavy rainfall events becoming more frequent during any season;
- changes in urban hydrology, especially regarding groundwater level and infiltration (ASHLEY et al. 2005);
- the increase of urbanisation and urban creep: in United Kingdom the urban population is expected to increase by 0.73 per cent per year from 2015 until 2020 (World Urbanization Prospects: The 2009 Revision).

- The deterioration of existing sewer systems and changes in local flood pathways and urban form (Review of Existing Private Sewers and Drains in England, Defra 2007).

These aspects will then increase the number of flooding in urban areas which is, considering all the water-related disasters over a 30 year period, already between the most frequent episodes, as Figure 1 illustrates.

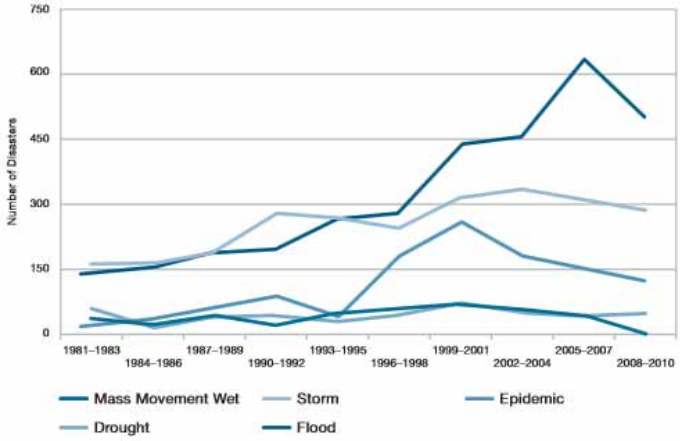


Figure 1: Trends in water-related disasters. Source: based on EM-DAT/CRED

Flooding can affect urban areas in both developed and developing countries. Cities which have experienced recent, large scale urban flooding problems include Bangkok, Thailand and Dhaka, Bangladesh (CHUSIT et al. 2001). In 2002 central London recorded an inch (25 mm) of rain in 30 minutes, resulting in the closure of 5 mainline railway stations, and considerable disruption (Flooding in London, 2002). In 2007, Hull suffered considerable flooding disruption and more than 10,500 homes were evacuated due to surface water (COULTHARD et al., 2007).

To mitigate these effects pluvial flooding models aim to predict urban areas most at risk of flooding and potentially provide warning to residents. However, such models are inherently difficult to verify due to the difficultly of acquiring reliable data during floods.

Hydraulic models (e.g. LEANDRO et al, 2008) have been developed which couple below ground pipe flow with shallow surface flow via interaction nodes (i.e. manholes/gullies). Such models can be used to evaluate the flood risk of specific urban areas, plan for asset improvement and investment and potentially provide flood warnings in the case of incoming heavy rainfall events. However these models are difficult to validate due to the paucity of data in real flood conditions. In peculiar the uncertainties caused by complex 3D flow fields at the interface between surface and sub-surface flows has not been examined (DJORDJEVIC et al., 2005). These interfaces are usually represented by uncalibrated weir or orifice equations, designed for use in steady flow, where energy losses are accounted for by a simple discharge coefficient (i.e. assumed constant with flow conditions). As such models are now being utilised in practice (e.g. InfoWorks CS 2D, SWMM, SIPSON), a potential improvement in modelling accuracy via experimental calibration will have significant benefits in terms of asset investment and the evaluation of flood risk.

AIMS

The aim of this work is to experimentally investigate the exchange of flows above and below ground urban floods.

This project is organised according to the following structure:

- Describe the concepts of urban flooding, including causes and factors that will increase this phenomenon in the future.

- Explain the technique of the Real Time Control for Urban Drainage Systems with the illustration of real applications and the help that computer models provide for the analysis 1D-1D / 1D-2D.
- Develop an experimental facility suitable for the comparison between physical results and computer model results.
- Determine discharge coefficients and provide a review of the performance of existing predictive models when tested against the experimental data.
- Develop a PIV system for comparison between 3D digital maps and images of the real urban flood event in the physical model.

MATERIAL & METHODS

This work has considered the development, construction and testing of a unique laboratory model of a sewer network coupled with an urban surface.
The physical model has been constructed in the laboratory of the University of Sheffield. The laboratory facility consists of three inlet pipes (A, B and C) and six manholes as shown in Figure 2. The six manholes are connected to each other by five circular pipes of two sizes. The pipes of the sewer system are 75 mm diameter, whilst the CSO (Combined Sewer Overflow) spill pipe is 100 mm diameter. Every manhole has an internal diameter of 240 mm. The water flows through this system from a constant depth header tank, with flows controlled by electronically actuated valves on each inlet pipe.
The physical model is fully instrumented with 21 calibrated series 5000 pressure sensors supplied by GEMS instruments that are used to record and log data in real time. The model also includes 3 Mag-900 flow meters, one on each inlet pipe. Flows into the system are controlled in real time via three calibrated butterfly valves at inlets A, B and C. The flow into each pipe is varied independently in real time. This allows scaled flows corresponding to each individual monitored rainfall event to be passed through the system.

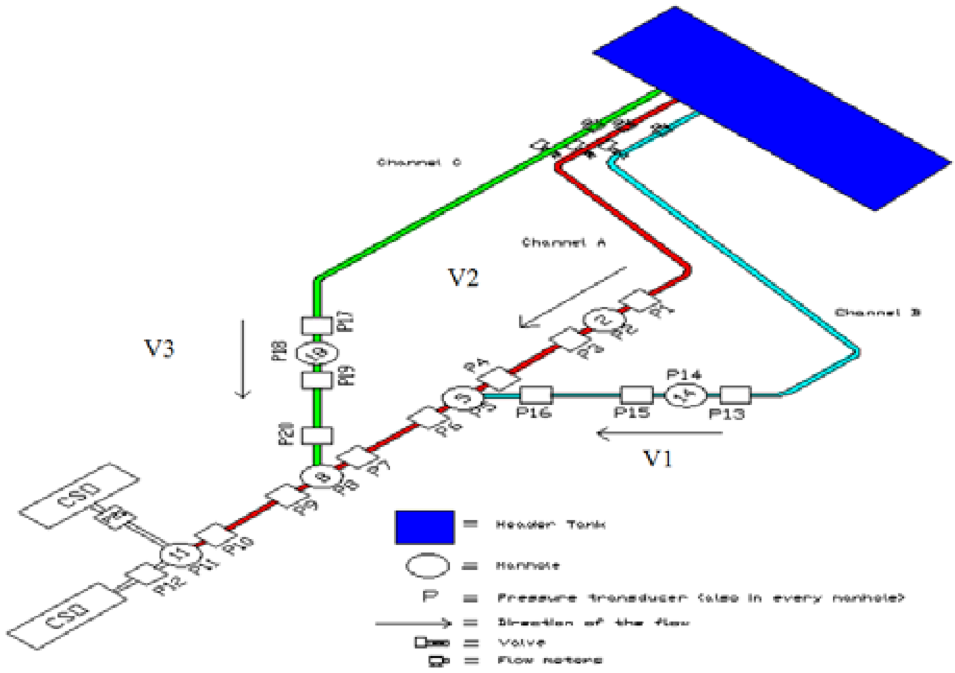


Figure 2: Scheme of the physical model.

The valves are actuated and data is collected using a National Instruments Data Acquisition System (DAQ) in conjunction with Labview software. Input signals for valve control can be directly programmed to reproduce scaled hydrographs derived from the InfoWorks model which include both dry weather flow components and wet weather responses derived from runoff volume and routing equations.

On the top of the pipe network, there is a preliminary urban surface with the slope of 1/1000. Just above the central pipe, in which 4 manholes in series are located the geometry of a street will be reproduced (width 1200 mm). Inflow and outflow of the above and below ground system can be controlled and monitored independently in real time and pressure at various points within the system is logged in real time. Scheme of the urban surface is illustrated in Figure 3.

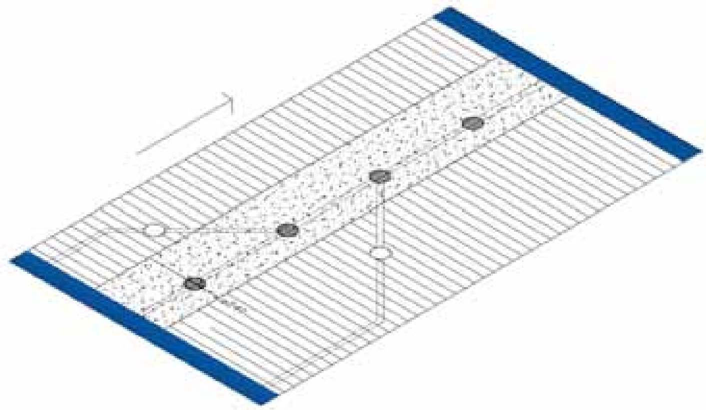
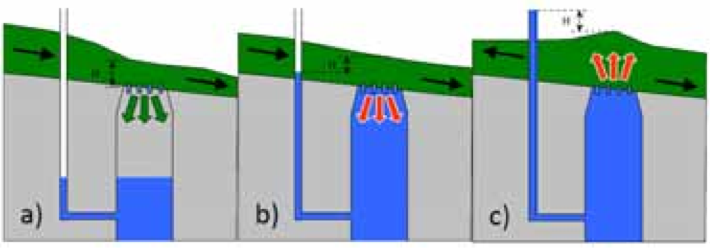


Figure 3: Scheme of the urban surface 1/1000.

In this work the behaviour of the manholes will be studied and analysed for the following hydraulic cases (Figure 4):



a) Free inflow, inlet as a weir
b) Submerged inflow, inlet as an orifice
c) Outflow (Djordjevic et al., 2005)

When a hydraulic head in a manhole is below the ground level (Figure 4a) it does not influence the flow through the inlet. Thus the inflow into the minor system can be described by a weir equation.

$$Q = \frac{2}{3} C_w W \sqrt{2g} (h_u - z_{crest})^{\frac{3}{2}}$$ - Free Weir Equation (4a)

When a head in the manhole is between the ground level and the water level on the surface (Figure 3b) the water still flows from the surface to the pipes, but now the orifice formula is proposed as best description of the flow.

$$Q = \frac{2}{3} C_w W \sqrt{2g} (h_u - z_{crest})(h_u - h_d)^{\frac{1}{2}}$$ - Submerged Weir Equation (4b)

Finally, water outflows from the underground system to the surface when the head in the manhole is above the water level on the street (Figure 4c), and again an orifice formula is proposed. Once the difference between the head in the manhole and the surface water level reaches a certain threshold value (large enough for the hydrodynamic force to lift up the manhole top) the equivalent orifice area increases.

$$Q = C_d A_0 \sqrt{2g(h_u - h_d)} \text{ - Orifice equation} \quad (4c)$$

Where :
h_u = upstream water level
h_d = downstream water level
z_{crest} = crest elevation
w = weir crest width
c_w = discharge coefficient

Equations for the discharge are derived based on the principles of energy conservation. These principles therefore contain assumptions such as steady flow 1D flow with energy losses due to turbulence taken into account via a constant discharge coefficient. Determination of the discharge coefficient for the weir and orifice is difficult because of the paucity experimental data available. By measuring flow rate in the above plus below ground system, the results will quantify the degree of exchange between the above and below ground systems and coefficients for the previous equations will be determined.

RESULTS AND DISCUSSION

The steps that have been completed to date include:

- A literary review of real time control for urban drainage system and urban flooding;
- Construction of the physical facility and the testing of all the electric and mechanical devices;
- Build a measurement using the interface Labview software to manage the data in real time in the physical model;
- Calibrate the flow control valve and the flow meters in order to establish a precise flow rate in the system that is capable of simulating flow hydrographs;
- A series of tests to study the behaviour of the system (pressure and depth) with changeable flow rates;
- Simulate real rainfall events with the InfoWorks software (using data available from April 2008 to June 2009), considering antecedent conditions;
- Reproduce those events scaled in the model and compare with the experimental simulations.
- Construction of a preliminary urban surface with the slope 1/1000 on the top of the rig.

Last steps will include the following activities which will complete the work:

- Study the interaction above/below ground urban floods with constant flow rates and changeable flow rates.
- Measure the flow dynamics of the surface of shallow water flows over a large measurement field. To do this, a simple and reliable method will be developed using Particle Image Velocimetry (PIV).
- Comparison 3D maps from software with real images to verify accuracy of digital modelling.

CALIBRATION EQUIPMENT

The three flow valves are directly controlled via an input current (mA) via the Labview control panel. To calibrate the valves, the relationship between signal and flow rate was defined by accurately measuring a range of 20 steady flow rates through each individual valve and defining a correlation against the valve opening signal. The calibration has been carried out in both partially full and surcharged pipes. In order to calibrate the pressure sensors, 20 different steady flow rate where passed through the physical model. At each flow rate, after a 300 second stabilisation period, the pressure transducer output in mA (with readings over another period of time of 300 seconds) and depth of water in mm in each manhole was recorded.
The correlation between sensor output and water depth is plotted to derive a linear calibration equation for the sensors. The range of the pressure sensors is 0-70mb, output is specified as 4-20mA. Figures 5a and 5b provide upstream view and downstream view of the central pipe A.

Figure 5a: Particular view of the central pipe.

Figure 5b: View from downstream.

RAINFALL SIMULATIONS

After having tested the physical model with steady flow simulations to determine the capacity of the sewer system, it has been tested also with a range of unsteady flow rates generated by real rainfall events simulated with InfoWorks software.

Rainfall events recorded in the catchment with durations of 15 ± 1, 30 ±2, 45 ±1 and 60 ± 2 minutes have been simulated in both the hydraulic and physical models (Table 1). These events have been recorded over a period of 15 months by a tipping bucket rain gauge. For simulation in the physical model, the resulting flows require downscaling to correctly reproduce Froude similitude within the model.

Table 1. Example of Rainfall Events re-produced in the physical model.

N of Event	Date	Duration	Average	Rainfall Depth
		(min)	(mm/h)	(mm)
1	11 Feb.'09	16	4	0.8
2	4 May '09	32	1.7	0.6
3	26 March '09	44	2.9	2.2
4	11 April '08	60	2.6	2.6

The physical model has been run many events and here are presented some examples for the input events described in Table 1. Figures 6 and 7 display example events reproduced which compare the measured results (physical model) and simulated results (hydraulic model). In the legend, “CM” is referring to Computer Model results, while PM is related to Physical Model results. Each chart is connected with the corrispondent rainfall intensity to show the marked relationship between peak of rainfall and peak flow.

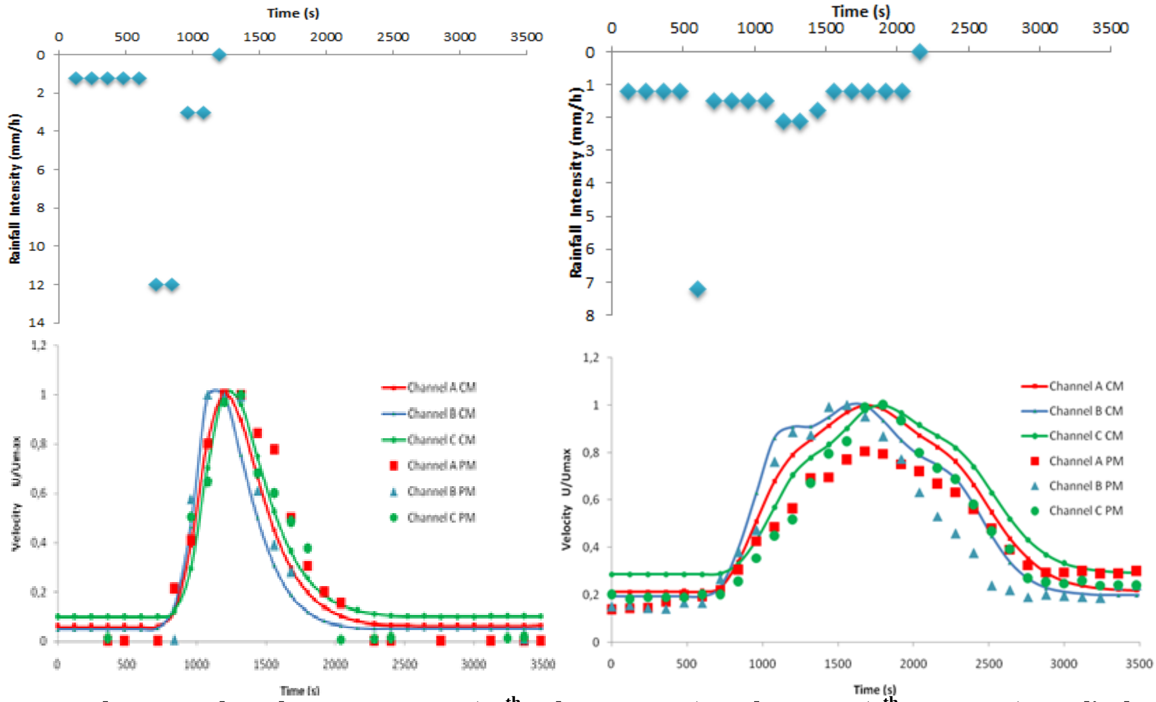


Figure 6a, 6b: Two selected events. Event 1 (11th February 2009) and Event 2 (4th May 2009) are displayed.

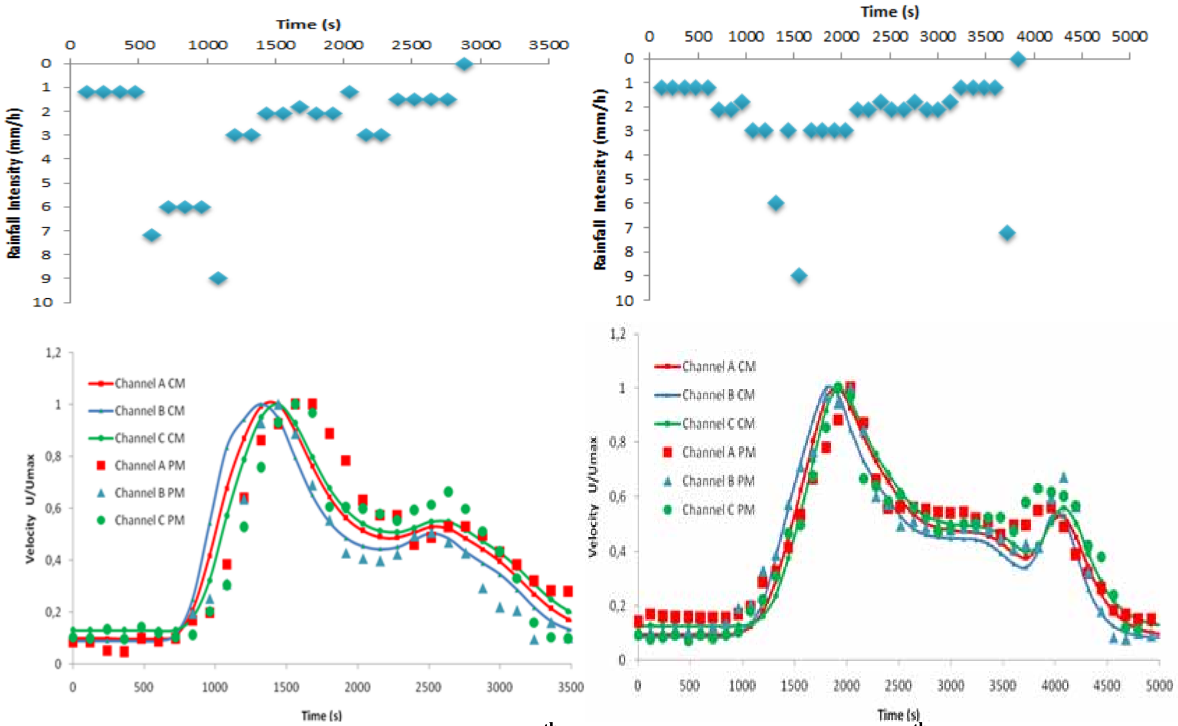


Figure 7a, 7b: Two selected events, Event 3 (26th March 2009) and Event 4 (11th April 2008), are displayed. Those events are respectively 44 and 60 minutes duration.

To determine an overall accuracy of this data, a multiple correlation coefficient R^2 has been calculated for each event using the formula described in Young et al. (1980) to measure how well the variables could have been predicted using a linear function of a set of other variables.
This parameter is therefore a normalized measure of the degree to which the model explains the data and if $R^2 = 1.0$ then the data are explained perfectly by the model while if $R^2 = 0.0$ the model has failed to represent the data.

$$R^2 = 1 - \left[\frac{\sum_{t=1,n}(m_t - p_t)^2}{\sum_{t=1,n} m_t^2}\right]$$

Where:
m_t = value measured in the physical model
p_t = value obtained from the computer model
N = the total number of samples in data set

Table 2. Values of R^2 for each test in each channel.

N. of Event	R^2 Channel A	R^2 Channel B	R^2 Channel C Date
1	0.827	0.792	0.810
2	0.966	0.936	0.937
3	0.983	0.954	0.952
4	0.955	0.957	0.969

Analysing R^2 coefficients and visually comparing the trend of the simulation, it is possible to declare that the physical model was able to reproduce real rainfall events simulated with InfoWorks software in terms of aim of this work. In fact authors wanted to provide a procedure that includes computer modelling and physical modelling which could allow engineers to verify existing software. This good re-production of the trend of real rainfall events enables the future steps of this research which includes the analysis of the coefficients that characterize the physical aspect when the water leaves the drainage/stormwater system in case of flooding, simulating event that can cause flooding on the streets with the water that flows onto a three-dimensional ground surface where the flow routes and paths are not well defined such as discharge from manholes.

CONCLUSIONS

The calibration of the physical model and the results obtained with the simulations indicate that simulations with large flow-rates to simulate the flooding of the water onto the streets may be assessed.
Future work (already started) therefore involves the assessment of the urban surface interaction and will allow the study of exchanging surcharge water. Flow in the pipe network can be utilized to identify hazardous flood zones and where high velocity occurs.
This is really important for the verification of existing discharge coefficients that can be found in literature and that are applied from engineers.
This aspect is essential in terms of planning strategies for reducing the risk of flooding, especially in urban areas. Cities without data and money to develop sewer system should rely in optimal solutions planned based on software. It is fundamental to confirm that the results are very accurate to avoid waste of money.

As previously mentioned, nowadays, despite the high safe standards reached by our society, there are still zones in the European Communities that are affected by flooding. These natural disasters cause human and economic losses (Fig. 8). This is the reason why the European Communities decided to undertake a wide plan to reduce and avoid these problems.

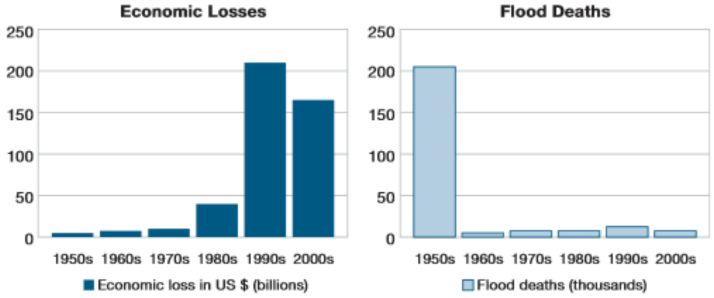


Figure 8: Reported economic losses and deaths. Source: based on EM-DAT/CRED.

This research deals with one purpose of the European Communities' action: understanding better the mechanism of flooding from sewers.

Developing countries are particularly vulnerable to these problems linked to climate change, inefficiency of existing structures and lack of money. Assistance in the form of research and capacity-building that enables them to prevent and react to growing problems is necessary.

European and International Nations are aiming to provide this assistance in many different terms focusing on different aspects:

- Governing water wisely: to ensure good governance, so that the involvement of the public and the interests of all stakeholders are included in the management of water resources.
- Protecting ecosystems: to ensure the integrity of ecosystems through sustainable water resources management.
- Managing risks: to provide security from floods, droughts, pollution and other water-related hazards.

This research will definitely provide benefits in terms of analysis of the risk through the use of computer models simulating flood from sewers into the above surface and vice versa. This can be really important for engineers who will be selected to develop new drainage systems for cities in developing countries. On the other hand, improving the accuracy of computer models can be definitely significant if the drainage system considered is related to a city which provides all the necessary information requested. For cities in developing countries, due to the lack of interaction between community and city administration in some cases, it is hard to obtain all the information needed by engineers such as future city developments that have to be considered in terms of planning new solutions.

Therefore, this lack of material and information can be a limitation for the use of modelling solutions for cities in developing countries.

I suggest that other aspects should be more incentivized in developing countries:

- Increase of public participation in the urban drainage management;
- Comprehensive project organization and clear allocation of responsibilities;
- Adequate urban land-use planning and enforcement;
- Capability to cover all phases and aspects of technical and non-structural planning.

Then, once the structural system is solid and regulations have been defined, the water management of each city regarding the flood risk should consider the following principles:

- Flood control evaluation should be done in the whole basin and not only in specific flow sections;
- More emphasis should be given to non-structural measures for flood plain control such as flood zoning, insurance and real time flood forecasting.

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